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A Helicopter Flight Laboratory Experience in an Undergraduate Helicopter Aeronautics Course

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List of Symbols

A	Rotor Disk Area	Q	Torque
b	Number of Blades	R	Rotor Radius
c	Blade Chord	V_{mp}	Speed for Minimum Power
C_{do}	Mean Profile Drag Coefficient	V_{mr}	Speed for Maximum Range
$C_{l\alpha}$	Section Lift Curve Slope	λ_i	Rotor Induced Inflow Ratio
C_{pi}	Induced Power Coefficient	λ_h	Rotor Induced Inflow Ratio at Hover
C_{po}	Profile Power Coefficient	μ	Advance Ratio
C_{pp}	Parasite Power Coefficient	σ	Rotor Solidity
f	Equivalent Flat Plate Area	Ω	Rotational Frequency of Rotor
k	Induced Power Factor		
K	Profile Power Factor		

Introduction

While courses on rotorcraft still remain less common than courses on fixed-wing aircraft at the undergraduate level, several prominent schools do feature such courses. A review of the course offerings at 16 undergraduate institutions offering Aerospace Engineering programs shows that five offer at least one course related to vertical flight. In addition, growing interest in unmanned aircraft with vertical takeoff and landing capability is driving increased interest in the topic. A common feature of any engineering program is to reinforce theory learned in a classroom environment with hands-on applications in the form of laboratory exercises. For rotorcraft courses, simulation, wind tunnel experiments, and whirl-stands all have their role in supplementing classroom instruction. The purpose of this paper is to demonstrate the application of a laboratory conducted in an actual helicopter as one way to reinforce classroom instruction, provide practical context for the study of helicopters, and to inspire students.

Background

The Mechanical Engineering Program at West Point has offered courses in Aeronautical Engineering in some form or another since the 1920s. The leadership at the institution decided early on that instructions for these courses be supplemented with as much practical application as possible. The form of that hands-on application has certainly changed over the decades, but since 1970 a hallmark of the program is the use of aircraft for in-flight laboratory exercises. These lab exercises included fixed-wing laboratories in a T-41 (Cessna 172) and eventually Cessna 182 aircraft as well as the rotary-wing labs in a UH-1 and now UH-72 (Airbus Eurocopter EC145) helicopter. The fixed-wing flight lab program and early rotary-wing laboratories were discussed in a previous article.[1] The purpose of this article is to focus more

closely on the rotary-wing lab program and outline updates since the aircraft used for the lab changed.

There are three Aeronautical Engineering courses offered at West Point, which as of 2016 form the nucleus of an Aeronautical Engineering minor. They are ME387: Introduction to Applied Aerodynamics, ME481: Aircraft Performance and Stability and the course related to this article: ME388 Helicopter Aeronautics. Evidence of the course offering goes back to at least 1973. The current course description in the catalog is as follows:

> The aerodynamics of helicopter flight is analyzed for hover, translating, and partial power flight. Theory and experimental results are used to predict aircraft performance. The course analyzes the dynamic response of the rotor system and the performance aspects of the vehicle as a whole. This is followed by a design workshop, during which cadets complete the initial sizing of a helicopter to meet mission requirements. The course includes one flight lab in a helicopter, a laboratory examining rotor power and thrust using a whirl stand apparatus, and one field trip to a commercial helicopter company.[2]

Overall, the course offers an overview of many of the facets of helicopter aeronautics to include aerodynamics in a hover, forward flight, and autorotation; performance, and sizing analysis within the context of a design problem. The course introduces the topics of control power and rotor dynamics but does not offer a full treatment of helicopter stability and control.

Implementation and Sample Results

The laboratory exercise is executed over a period of two days with up to three backup dates planned for weather problems. The pilots and aircraft belong to a detachment that provides administrative and VIP support to the Academy. Prior to the actual conduct of the lab exercise the instructor for the course meets with the lab pilots to review administrative and logistical requirements and review the lab procedures. The Instructor is also a qualified helicopter pilot but does not operate the aircraft during the course of the lab exercise in order to provide better oversight of the students as they gather data and participate in the lab experience.

The aircraft used for the labs is a UH-72A Lakota, which is a military version of the Airbus EC-145 twin-engine, single main-rotor helicopter. The aircraft has a maximum gross weight of just over 8,000 pounds, seating capacity for up to nine personnel, and features two Turbomeca Arriel 2 turboshaft engines.[3] Student capacity is limited to four in order to keep the lab groups smaller which allows each student time to ask questions and see the flight instruments during the conduct of the lab. The Instructor sits in the back with the students to help guide the procedures and narrate certain demonstrations when the group is not actively taking data.

The lab exercise begins with the aircraft shut down. The instructor and aircrew provide an overview of the major components on the aircraft and focus on particular design features related to course content. For example, students can examine the hingeless rotor system up close, which is linked to a previous lesson on control power. They also see the placement of items like the pitot tubes and link that concept back to previous content in fluid mechanics. Finally, the students are able to examine and discuss practical design considerations such as the

placement of the tailboom with respect to the fuselage. The UH-72 was designed to serve in a medical evacuation role so features clamshell doors in the back of the fuselage, necessitating a high placement of the tailboom. Concepts such as this are linked to their general engineering design course content.

Once the students receive a safety briefing and load the aircraft, the actual lab procedures begin. The first stage of the lab involves a demonstration of the anti-torque requirements of a single main rotor helicopter with a standard counter-clockwise rotation. The pilot brings the aircraft to a five foot hover and orients the student to a landmark in front of the aircraft. He or she then holds the pedals at a specific position and then abruptly increases collective pitch. As the aircraft climbs, the nose also yaws to the right without the requisite increase in tail rotor pitch. This maneuver reinforces the counter-torque lesson in the course. If wind conditions permit, the pilot will also position the aircraft such that the wind strikes the aircraft from the aft, left quadrant. At this point, the aircraft will tend to yaw sporadically, demonstrating the loss of tail rotor effectiveness that can be encountered as the aircraft experiences a weathervane effect, or the tail rotor experiences vortex ring state.

The next demonstration involves the concepts of Effective Translational Lift (ETL) and Transverse Flow. The pilot gradually increases forward cyclic, transitioning from hover to slow forward flight. Once the aircraft experiences the vibrations associated with transverse flow through the rotor, he or she will maintain that forward airspeed while the Instructor discusses the different inflow angles associated with the fore and aft halves of the rotor disk in this flight condition. The pilot then adds additional forward cyclic, without an increase in collective pitch, until the aircraft accelerates and experiences a significant decrease in induced power requirements known typically as ETL.

Once the pilot maneuvers the aircraft out of the terrain flight environment, the students will take their first set of data. The pilot continues to climb at progressively faster airspeeds in 15 knot increments. At each new airspeed, the pilot sustains the airspeed for at least 1,000 feet of ascent. During that time, the students record the time it takes to climb 1,000 feet and note the vertical speed indicated in the cockpit at roughly the midpoint of the climb. The entire maneuver is conducted at a constant torque setting and in the same direction to eliminate changes in power or wind direction as variables. The purpose of this part of the lab is to understand the relationship between forward airspeed and excess power. An example of the results for this portion of the lab appears in Figure 1.

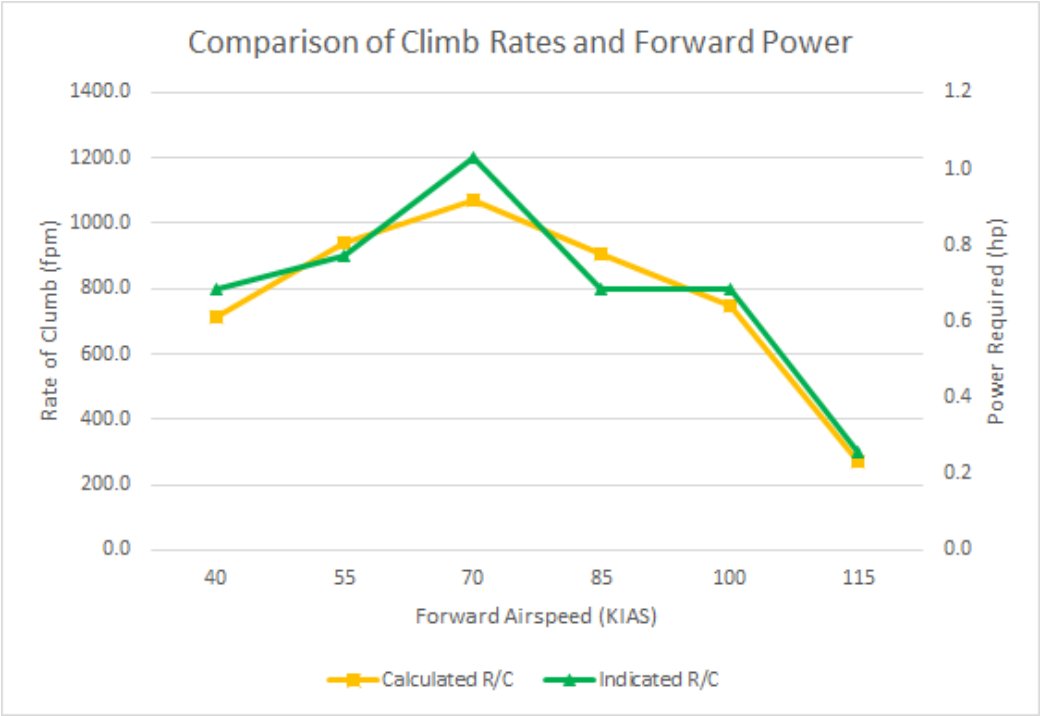

Figure 1

The excess power portion reinforces the next part of the laboratory, which is the power required versus forward airspeed in steady, level flight. During this phase, the pilot establishes the aircraft in level flight at progressively slower airspeeds in 15 knot increments again. At each increment, students record the pressure altitude, outside air temperature, fuel remaining, indicated airspeed, and engine torque. The pressure altitude and temperature data is used to calculate air density, and the fuel remaining data is used to determine the actual gross weight of the aircraft during the maneuver.

The purpose of this portion of the lab is to compare the actual power requirements in forward flight, with theoretical predictions. The theoretical predictions are based on momentum theory analysis relationships for induced, profile, and parasite power as discussed in Leishman's text: Principles of Helicopter Aerodynamics, 2nd Edition.[4] This text is used for the entire course. The parameters used to predict power requirements for the aircraft appear below in Table 1.

Table 1

Parameter	Value	Units
Section Lift Curve Slope (C_{l_α})	2π	per radian
Induced Power Factor (k)	1.15	n/a
Profile Power Factor (K)	4.6	n/a
Mean Profile Drag Coefficient (C_{d_o})	0.0102	n/a
Equivalent Flat Plate Drag Area (f)	21	ft^2
Rotational Frequency (Ω)	383	RPM
Rotor Radius (R)	18.04	Ft
Rotor Chord (c)	1.025	Ft
Number of Blades (b)	4	n/a

In order to predict the performance requirements for the aircraft, one key assumption is made in order to determine an analytical solution for inflow. The angle between the tip path plane of the rotor disk and the freestream velocity is assumed to be zero. This is because the angle cannot be accurately predicted without knowledge of the actual thrust and drag on the aircraft. As a result, the induced velocity can be analytically predicted at the various airspeeds based on an approximate relationship for the non-dimensional inflow ratio found in Leishman's text which appears as Equation 1. The calculations to determine induced, profile and parasite power predictions in non-dimensional form appear respectively as Equation 2 through Equation 4.

$$\frac{\lambda_i}{\lambda_h} = \left[\sqrt{\frac{1}{4}\left(\frac{\mu}{\lambda_h}\right)^4 + 1} - \frac{1}{2}\left(\frac{\mu}{\lambda_h}\right)^2\right]^{\frac{1}{2}}$$

Equation 1

$$C_{P_i} = \frac{kC_T^2}{2\sqrt{\lambda^2 + \mu^2}}$$

Equation 2

$$C_{P_o} = \frac{\sigma C_{d_o}}{8}(1 + K\mu^2)$$

Equation 3

$$C_{P_P} = \frac{1}{2}\left(\frac{f}{A}\right)\mu^3$$

Equation 4

Students use the torque data from the lab to determine actual power at the various airspeeds. To do this, they use information from the engine manufacturer to convert torque readings to power settings. These equations are below in Equation 5 through Equation 7. Once complete they compare the total power predicted by theoretical means to the actual power recorded during the flight and determine the difference. Examples of the results appears in Figure 2 and Figure 3. The first figure only shows the total power predicted vs actual and the difference. The second shows the components of power and the total power. Students are asked to comment on the fact that theoretical calculations typically under-predict actual power requirements by 10-15%. Typical discussions focus on the requirements of the tail rotor, which can consume approximately 5% of the main rotor power, according to Leishman, and other power requirements driven by the transmission to include generators, pumps, and other accessories.[5]

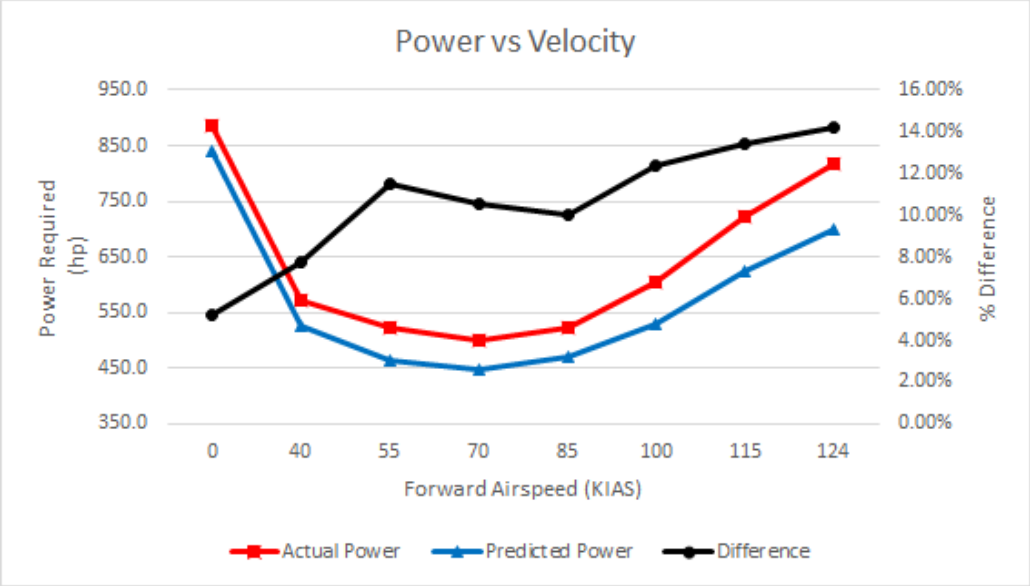

Figure 2

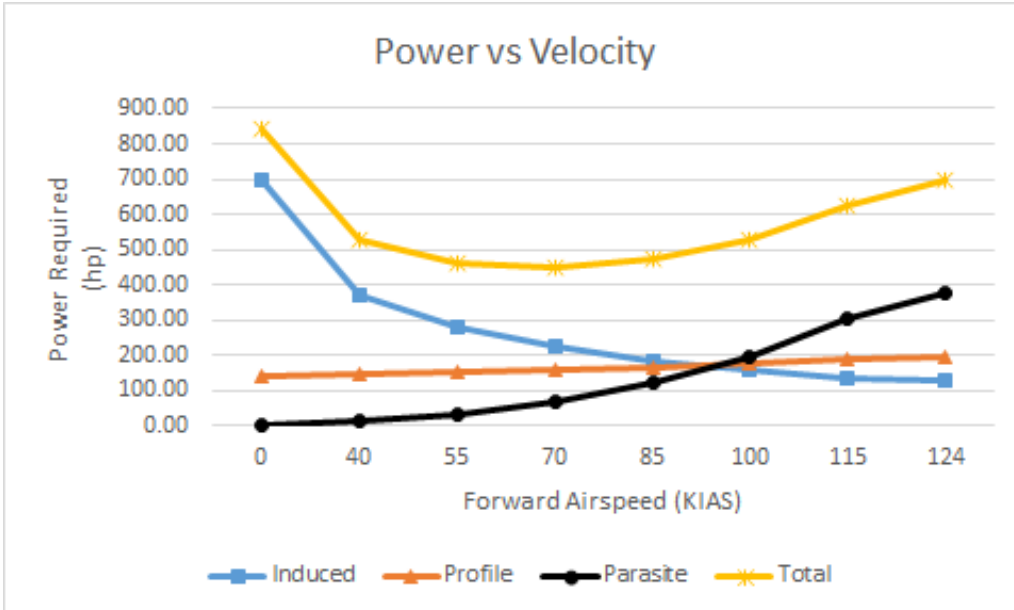

Figure 3

Engine Torque (Q): Q [ft-lbf] = %Q (*cockpit indication*) * 1020

Equation 5

Engine RPM (Ω): Ω_{ENGINE} = 6000 RPM

Equation 6

Shaft Power Required:

$$SHP = \frac{Q(ft \cdot lbf) \cdot \Omega_{ENGINE}\left(\frac{rad}{sec}\right)}{550 \cdot \left(\frac{\frac{ft \cdot lbf}{sec}}{hp}\right)}$$

Equation 7

The students then plot the actual power determined experimentally on the same axis as their climb data to reinforce the idea that maximum rates of climb coincide with minimum power requirements. An example appears in Figure 4. The students also use their power curve to determine graphically where the velocity for maximum endurance and maximum range would occur and compare that to theoretical predictions, based on the equations below as Equation 8and Equation 9.

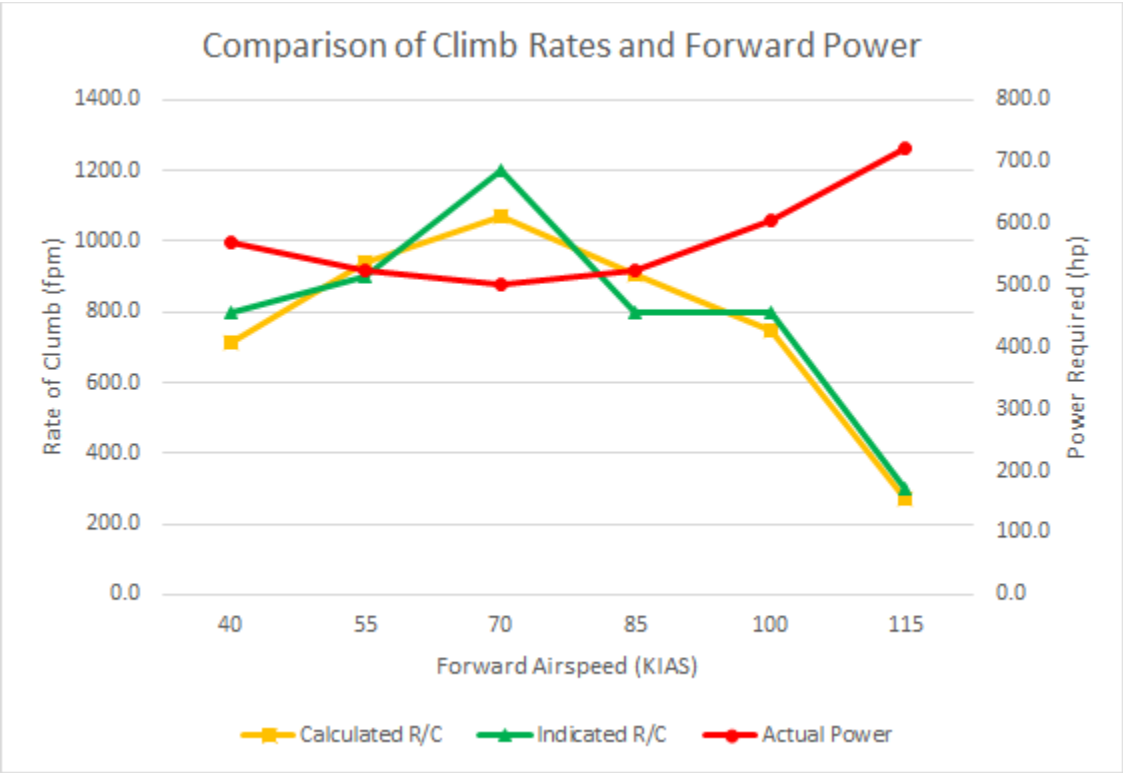

Figure 4

$$V_{mp} = \sqrt{\frac{W}{2\rho A}}\left(\frac{4k}{3\frac{f}{A}}\right)^{\frac{1}{4}}$$

Equation 8

$$V_{mr} = \sqrt{\frac{W}{2\rho A}}\left(\frac{4k}{\frac{f}{A}}\right)^{\frac{1}{4}}$$

Equation 9

After the level flight data collection, the pilot will demonstrate the limitations on forward airspeed based on dissymmetry of lift simply by accelerating the aircraft to the maximum speed possible and noting the vibrations that occur mainly due to retreating blade stall. The final demonstration is conducted enroute to the start point by flying in a terrain flight profile and demonstrating the responsive nature of the control system on the UH-72. The students previously observed the hingeless rotor and can now gain a better sense of the reaction time and roll rate generated by very small cyclic inputs from the pilot.

The final data set the students collect is related to hover performance. The pilot will execute an approach to an out of ground effect (OGE) hover. Students then record the aircraft

skid height, based on radar altimeter readings, and engine torque. This process is repeated at altitudes of 75, 30, 25, 20, 15, 10 and 5 feet. Based on the dimensions of the aircraft, students can convert skid height to the height above ground of the rotor disk, and convert torque to power settings using the procedures previously described. The students then compare the actual power required to hover at various rotor heights to theoretical predictions based on work by Betz, from his 1937 model, and Hayden, from his 1976 model. An example of that analysis appears in Figure 5. The Betz model over-predicts power requirements when analyzed in this manner and is not shown for scaling purposes. However, the Hayden approximation provides an accurate representation of the advantage associated with In Ground Effect (IGE) hover.

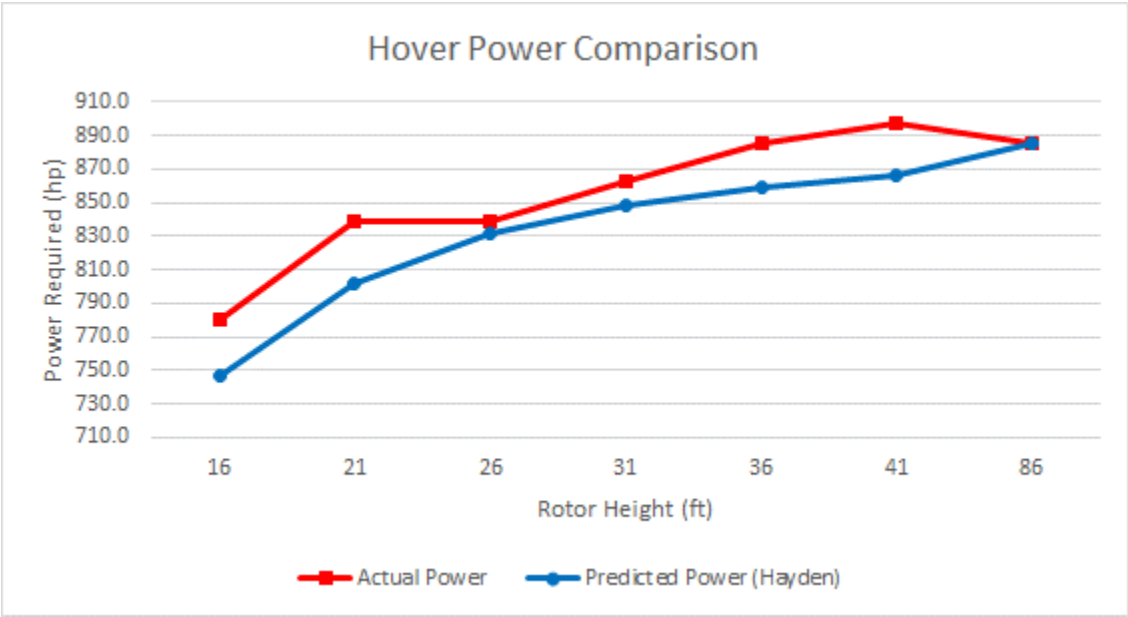

Figure 5

Student Feedback

Both anecdotal and formal feedback on the flight lab experience continues to be very positive. Most students cite the lab as the highlight of the course and an opportunity to link together many of the concepts they learned in the course in a real and practical way. Course end feedback from the most recent course offering appears below in Figure 6. Students are asked a series of questions and rate their agreement on a typical Likert-type scale with 1 being Strongly Disagree and 5 being Strongly Agree. The question related to the flight lab features the most positive feedback and an examination of multiple years of data reveals a similar trend so this offering is not an anomaly. What is interesting about the results of the question is that it is does not ask whether students enjoyed the lab or were excited about the lab. Instead, the question determines whether the lab contributed to their learning and the result is overwhelmingly positive.

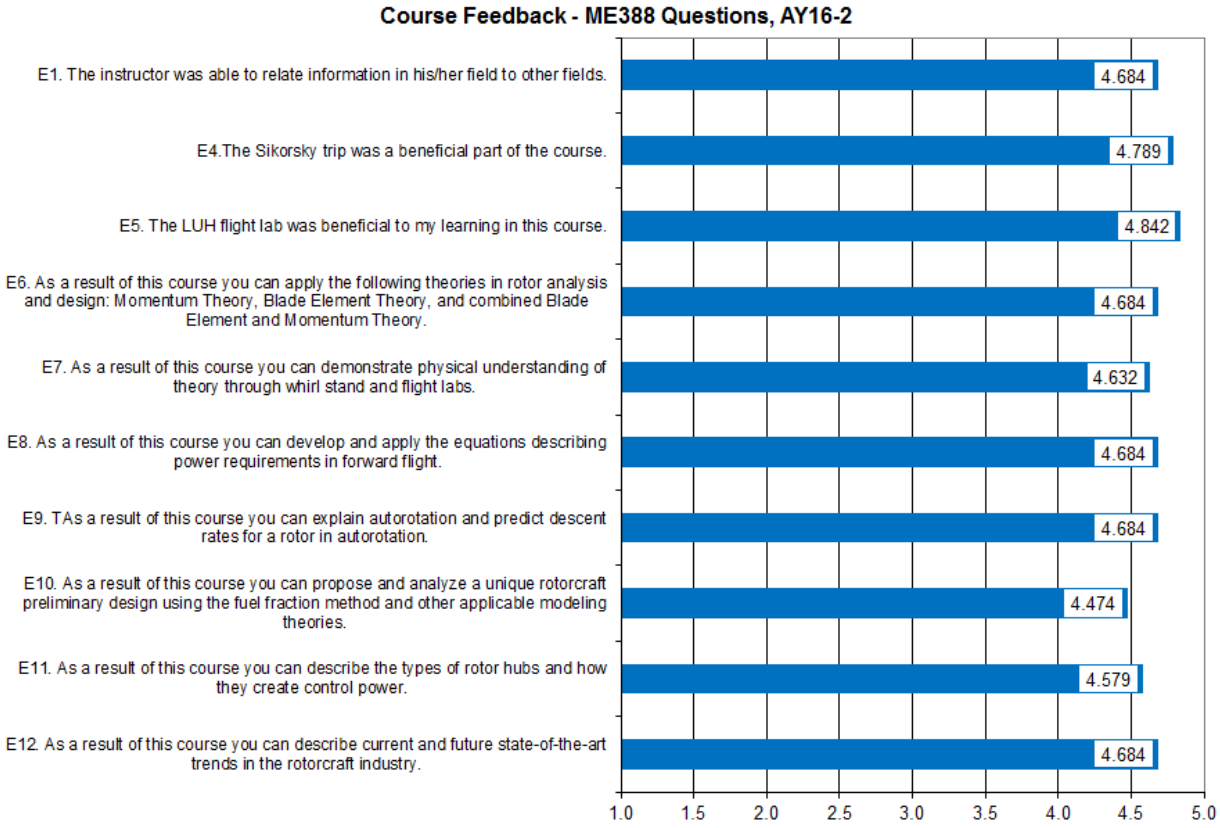

Figure 6

It is the author's intent to tailor future course end feedback questions to focus on specific aspects of the lab experience to determine what course objectives are best reinforced by the experience. That feedback will enable future labs to potentially strengthen aspects of the lab that are not serving as well to reinforce concepts learned in the classroom.

Conclusions and Summary

The helicopter flight lab remains a strong component of the ME388 course offering and along with the fixed-wing flight laboratories offered in the program, remains a hallmark of the Aeronautical Engineering experience in the department. Having said that, the author recognizes that it is not feasible or practical for some institutions to operate a helicopter in the same way due to costs, insurance and safety concerns, pilot availability, space availability and other concerns.

Despite these potential limitations, the procedures described above are performed in a helicopter with no special limitation and by a pilot with no special training or experimental test pilot qualifications. The data obtained during the conduct of the test is all from standard flight

instruments, with the possible exception of the radar altimeter which is not featured on all helicopters. However, the lack of a radar altimeter could be overcome with the use of a standard altimeter and knowledge of the field elevation.

Based on these facts, it could be possible for an institution to rent an aircraft for limited periods to conduct an exercise similar to the one described above for students who are enrolled in a rotorcraft-related course. The benefits, in terms of practical understanding of a complex system, reinforcement of theory with experimental testing, and in simply inspiring students to better understand a complex and beautiful machine is immeasurable.

In addition to the laboratory procedures described, the department is exploring ways to increase the use of the fixed and rotary-wing aircraft for independent research projects beyond the scope of the three aeronautical engineering courses. An independent system that incorporates inertial and position data with respect to time is available and could be used in conjunction with students and faculty from other institutions, if there is data of interest.

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[1] Crawford, Grant, et al. "The United States Military Academy Flight Laboratory Program a Hands-On Approach to Engineering Education." American Society of Engineering Education Annual Convention. Portland, OR, 2005.
[2] The United States Military Academy. "Academic Program Curriculum and Course Descriptions." West Point, NY: Office of the Dean, 2016.
[3] Airbus Helicopters. EC145 Specifications. 29 November 2016. http://airbushelicoptersinc.com/products/EC145T2-specs.asp
[4] Leishman, J. Gordon. Principles of Helicopter Aerodynamics. Second. New York: Cambridge University Press, 2006.
[5] Ibid.